NISTIR 6327

Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

Report from the NIST/ACI/ASTM Workshop held in Gaithersburg, MD on November 9-10, 1998

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concrete. The probe has four anodes at different distances from the surface; using the time for corrosion observed at each anode, the model can estimate the chloride profile at any time and predict the initiation period if the thickness of cover is known. For existing concrete, required information about the ingress of chloride can be obtained by the method of inverse cores [10]. In this method, a core cut from the concrete is put back in place with the virgin part exposed to the environment; the ingress into the virgin surface is followed by measurements made at suitable intervals.

The chloride profile is characterized by four parameters – exposure time, t; surface ordinate (i.e., the chloride concentration at the surface), C_s; the initial chloride content of the concrete, C_i; and the diffusion coefficient, $D = a^2 / \pi t$, where a is the distance that chloride would have penetrated if the chloride concentration gradient was constant and had the value of the gradient at the concrete surface. The surface chloride content changes with time and the distribution depends on the direction of the prevailing wind and the distance above sea level. Also, for structures on the seashore, distance from the shore influences chloride ingress.

Penetration of chloride ions into concrete is affected by the heterogeneity of the material; it occurs through defects and the cement matrix. The potential diffusion coefficient can be determined as a function of. *w/c* ratio and concrete maturity using the NT Build 443 test method. For supplementary binding materials such as fly ash and blastfurnace slag, the binder's *factor of efficiency* is the mass of cement that can replace 1 kg of the binder without changing the chloride diffusivity of the concrete.

Examination of concrete specimens exposed to seawater at the Träslövsläge Marine Exposure Station provided data on chloride ingress; the parameters were: environments (marine atmosphere, splash zone, submerged), concrete composition (4 types of cement; 2 types of silica fume; 2 types of fly ash; $0.25 \leq w/b \leq 0.75$), and exposure periods from about 6 months to 5 years.

Service lifetime prediction by the HETEK method involves a 10-step spread-sheet calculation. It is described, and examples of initiation time predictions are given, in Reference [11]. The predicted initiation times were comparable to those made by Clifton's model [12] (e.g., Clifton, 30 years; HETEK, 25 years). Estimates of the parameters of the HETEK model were made using Mejlbro's Lambda functions [13].

Some other references to the work of Poulsen and his colleagues are [14,15,16].

2.5 MODELLING CHLORIDE INGRESS BY THE COMBINED PROCESSES OF DIFFUSION AND CONVECTION

Michael Thomas, University of Toronto, Canada (with Evan Bentz)

The University of Toronto (U of T) model [17] was developed by Bentz and Thomas. Their purpose was to provide a model that would be useful to engineers. The specific application was for reinforced concrete tunnel lining sections. The WINDOWS-based model addresses chloride ingress by diffusion, wicking, and permeability, with positive pressure heads, evaporation, convection, and chloride binding being taken into account. For wicking, the Buenfeld model [18] was adopted.

Input parameters in the U of T model are: surface concentration, diffusion coefficient and its change with time, activation energy of the diffusion process, the initial chloride profile, permeation coefficient and its change with time, a viscosity correction, binding coefficients, porosity, and the temperature profile. The output is the chloride (total or free) concentration profile at any selected time interval. The model was calibrated using Bamforth's data from OPC (ordinary portland cement) concrete blocks that the Taywood Company had exposed on the shore of the English Channel above the high-tide level; some of the blocks were of fly-ash-containing concrete. Chloride binding was represented by either the Langmuir isotherm or the Freundlich isotherm, and diffusion coefficients were determined for OPC and fly ash concretes.

The governing equation, and equations for chloride binding, diffusion coefficient, and hydraulic conductivity, follow.

The governing equation is:

$$dC_f/dt = D \, . \, d^2C_f/dx - v_{avg} \, . \, dC_f/dx \qquad (1)$$

where C_f = 'free' Cl in solution; D = diffusion coefficient; and v_{avg} = average linear velocity, which is given by:

$$v_{avg} = Q/n \, . \, A = -(k/n) \, . \, (dh/dx) \qquad (2)$$

with Q = flow rate; n = porosity; A = cross-sectional area; k = hydraulic conductivity (permeability); and h = hydraulic head.

The alternative isotherms used to represent chloride binding were:

the Langmuir isotherm: $$C_b = \alpha \, . \, C_f/(1 + \beta \, . C_f) \qquad (3)$$

and the Freundlich isotherm: $$C_b = \alpha \, . \, C_f^{-\beta} \qquad (4)$$

where C_b = concentration of bound chloride; and α and β = binding coefficients.

The diffusion coefficient, $D(t,T)$, at time t and temperature T, is given by:

$$D(t,T) = D_{ref} \, . \, (t_{ref}/t)^m \, . \, exp[(U/R) \, . \, (T_{ref}^{-1} - T^{-1})] \qquad (5)$$

where D_{ref} = diffusion coefficient at a reference time t_{ref} and temperature T_{ref}; m = a constant (depends on mixture proportions); U = activation energy of the diffusion process; and R = the gas constant; (the temperatures are in degrees Kelvin).

The hydraulic conductivity is:

$$k(t,T) = (k_{ref}/Z) \, . \, (t_{ref}/t)^r \qquad (6)$$

where $k(t,T)$ = permeability at time t and temperature T; k_{ref} = permeability at time t_{ref} and temperature T_{ref}; Z = viscosity temperature correction factor; and r = a constant (depends on mixture proportions), To facilitate its use, the model provides default values for quantities for which actual data may not be available. As can be seen from the plots in Figure 1, the model appears to provide a good fit to data for OPC concrete. Comparable results have been obtained for concretes containing blast furnace slag and fly ash.

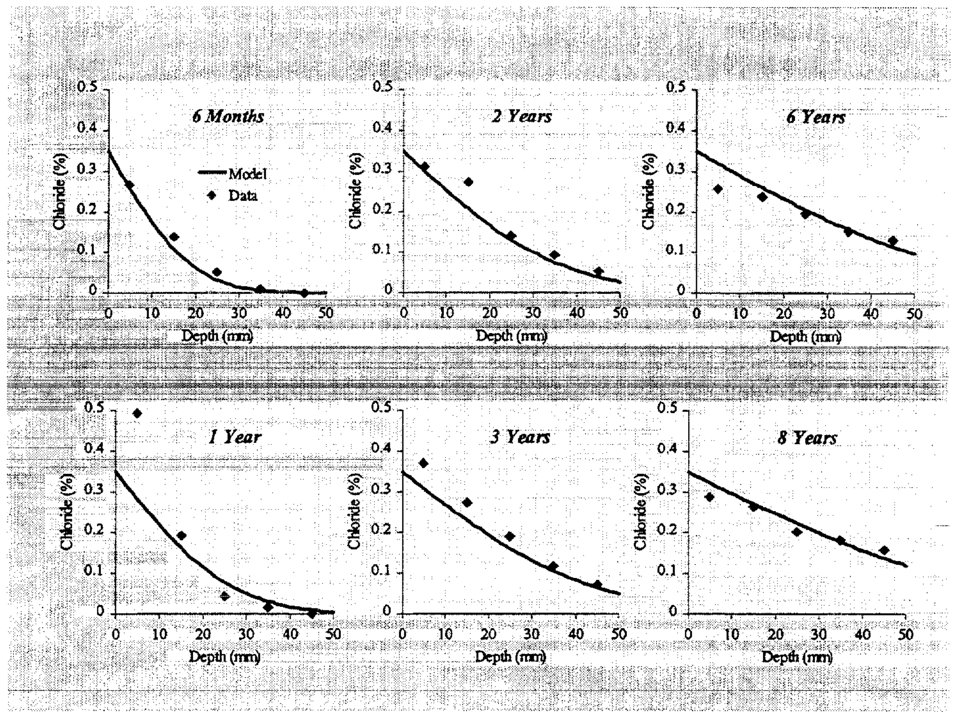

Figure 1. Comparison between U of T Model outputs and experimental data

2.6 MODELING ION TRANSPORT IN CEMENT-BASED MATERIALS
Jacques Marchand, Laval University, Canada (with E. Samson and Y. Maltais)

Over the past few years, the mechanisms of ionic transport in cement systems have been the subject of a great deal of attention. Most of the reports published on the topic have clearly emphasized the intricate nature of the problem. Given the number of parameters involved, the process of ionic transport cannot be described by analytical models, and numerical modeling is required.

The main features of a numerical model that predicts the mechanisms of ionic transport in reactive porous media were described in the presentation. An important original feature of the model is that it accounts for the electrical coupling (diffusion potential) between the various species in solution.

The model is divided into four parts: ionic diffusion, moisture transport, chemical reactions, and chemical damage. The transport of ions by diffusion is modeled by solving the extended